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Observation of delayed alignment in N=Z nuclei ^{72}Kr, ^{76}Sr and ^{80}Zr

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Excited states of the $N = Z$ nuclei ^{72}Kr, ^{76}Sr and ^{80}Zr have been studied in a series of experiments involving Gammasphere plus Microball, and Gammasphere plus the Argonne Fragment Mass Analyzer. The ground state band of ^{72}Kr has been extended to a spin of (26^+), and a very pronounced delay in the alignment of $g_{9/2}$ particles is evident. The ground state bands of ^{76}Sr and ^{80}Zr have been observed to spins 14^+ and 12^+, respectively, and also show evidence for delayed alignments. This delay in alignment may be a signature for neutron-proton pairing correlations.

1. INTRODUCTION

Nuclei in the mass region with $N \approx Z$ and $A \approx 80$ exhibit dramatic changes in nuclear shape with the addition or subtraction of only a few nucleons. For example, ^{68}Se [1] has the characteristics of an oblate shape, ^{72}Kr [2] displays the properties of shape coexistence, and ^{78}Sr [3] exhibits the properties of a prolate rotor. That these changes in shape are so strongly dependent on the number of neutrons and protons provides a stringent test for nuclear models. The Cranked Shell Model (CSM) [4] has been very successful in both describing and predicting these shapes.

These $A \approx 80$ nuclei also provide the opportunity to study the effects of neutron-proton (*np*) pairing correlations, as the neutrons and protons are expected to occupy the same orbitals, providing maximum overlap of the neutron and proton wave functions. If there are observable effects of *np* pairing, the $N = Z$ nuclei of this mass region should be some of the best candidates to study. Unfortunately, there are both experimental and theoretical

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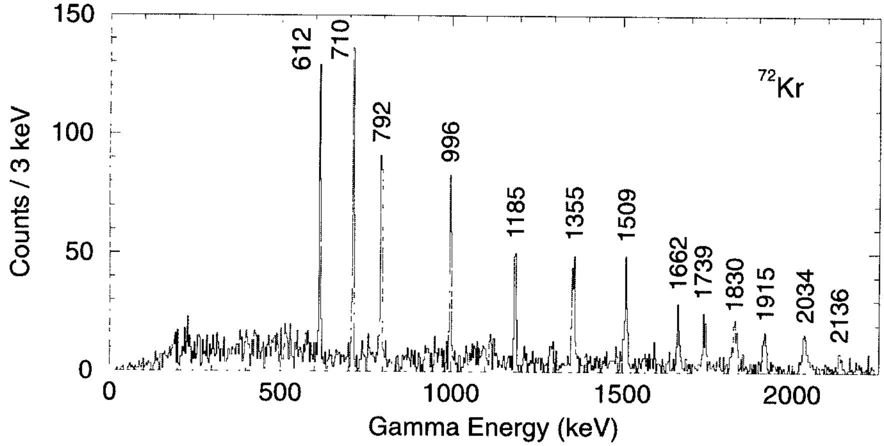

Fig.1. A sum of double-gated γ-ray spectra to highlight the ground state band of ^{72}Kr.

obstacles to overcome. A very limited number of stable beam and target combinations are available from which these $N = Z$ nuclei can be produced. When production is possible, the nuclei of interest are typically produced in the midst of a copious background of other undesired reaction channels that is orders of magnitude more intense than the nucleus under study. The other difficulty is to determine a specific experimental signature that will be an unambiguous characteristic of *np* pairing. One approach is to exploit the success of the CSM. The standard CSM does not include *np* pairing. Thus, if experimental results disagree with CSM predictions, the disagreement may be a result of *np* pairing effects which are not included in the calculations. It would then be necessary to introduce *np* pairing in the calculations to see if this could satisfactorily explain the experimental results.

2. STUDIES OF ^{72}Kr

One such discrepancy with theory has been observed in the study of ^{72}Kr [5] by deAngelis *et al.* which extended the ground state band of this nucleus to spin 14^+. When the kinematic moment of inertia is compared to those of the neighboring even-even Kr nuclei, and with the predictions of theory, the alignment of the $g_{9/2}$ particles is delayed relative to the expected frequency. It was suggested [5] that this delay in alignment might be a signature for *np* pairing correlations, since such pairs may be quite robust against rotation, delaying particle alignment until the Coriolis force strengthens at higher frequencies.

In the present work, we have extended the ground state band for ^{72}Kr to spin (26^+) in a study which utilized the Gammasphere array in conjunction with the Microball [6] charged particle detector array. The experiment was performed at the Argonne Tandem Linear Accelerator System (ATLAS) facility. A pure ^{40}Ca beam was delivered to the target by stripping the beam produced in the ECR source to a charge state of 19^+ in order to eliminate any possible ^{40}Ar contaminant. The nucleus of interest was produced in the 2α channel of the ^{40}Ca + ^{40}Ca reaction at a beam energy of 160 MeV. The Microball detector provided excellent channel selection. Fig. 1 shows a γ-ray spectrum depicting the members of the

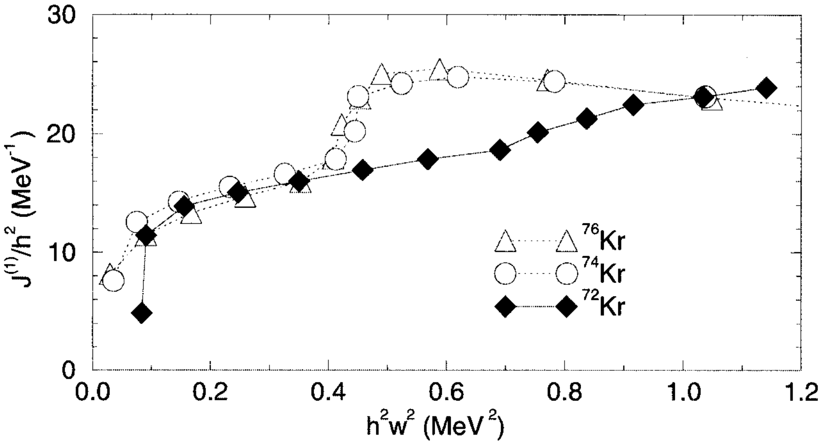

Fig. 2. The kinematic moments of inertia, $J^{(1)}$, versus $\hbar^2\omega^2$ for the nuclei ^{76,74,72}Kr.

ground state band. The spectrum was constructed from a sum of double-gated γ-ray spectra, each including one member of the band in the energy region from 612 keV to 1509 keV, and another member of the band in the energy region from 1662 keV to 1915 keV. This combination of gates produces the cleanest spectrum that includes only members of the ground state band. The data show a $16^+ \rightarrow 14^+$ transition with an energy of 1662 keV, rather than the 1368 keV reported by deAngelis. The 1368 keV transition appears to instead belong to a sideband.

Fig. 2 shows the kinematic moments of inertia as a function of the square of the frequency ($\hbar^2\omega^2$) for ^{76}Kr [7], ^{74}Kr [8] and ^{72}Kr. The moments of inertia for ^{74}Kr and ^{76}Kr are remarkably similar. Each shows an initial bend at low frequency due to coexisting shapes at low spin. The moments of inertia then show smooth behavior as the nucleus takes on a prolate shape. A sharp and sudden alignment is observed at $\hbar^2\omega^2 \sim 0.4$ MeV^2. For ^{74,76}Kr, this is due to the simultaneous alignment of $g_{9/2}$ neutrons and protons. The behavior of the moment of inertia of ^{72}Kr is quite similar to its neighbors at low frequency. However, the delay in particle alignment is much more dramatic than first observed by deAngelis. In fact, the moment of inertia shows a quite gradual alignment at high frequency. This result leads to two obvious questions: is this delay due to *np* pairing, and do other $N = Z$ nuclei show similarly delayed alignments?

3. STUDIES OF ^{76}Sr AND ^{80}Zr

The data for other even-even $N = Z$ nuclei in this mass region is quite sparse, primarily due to the difficulty of the relevant experiments. One method is the "Daresbury technique," [9] in which the nuclei are produced at the center of an array of γ-ray detectors, separated in A/Q as they pass through a mass analyzer, and then identified according to Z in an ionization chamber. This allows the γ-rays produced at the target to be correlated with an identified recoiling nucleus at the back of the mass separator. The best types of reactions for this technique are those that are highly inverse, such that the recoiling nuclei are produced with

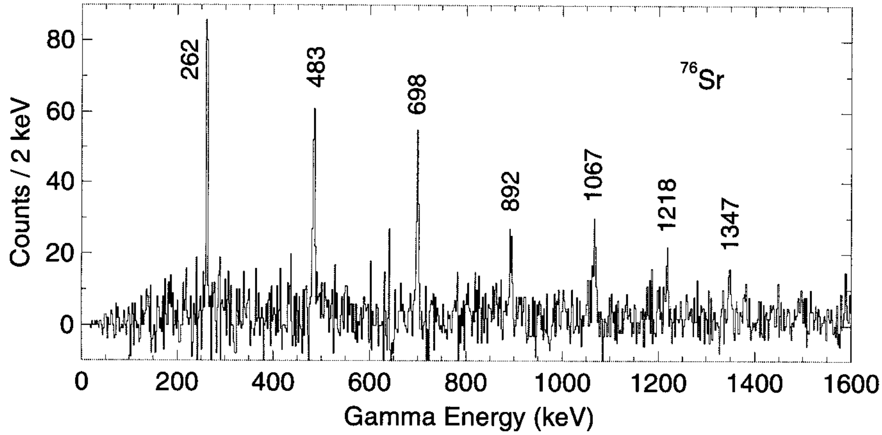

Fig. 3. The ground state band of ^{76}Sr as produced by a sum of γ-ray coincidence gates for recoils with $Z = 38$.

high velocities, and are emitted in a forward-focussed cone that is largely within the acceptance of the mass separator. Typical recoil velocities are on the order of 5% to 7% *c*, and allow for good *Z* identification in the ion chamber.

Excited states in the ^{76}Sr nucleus were populated in the ^{24}Mg(^{54}Fe,2*n*) reaction at a beam energy of 180 MeV. The experiment was performed at ATLAS, with γ-rays detected by 101 HPGe detectors of the Gammasphere array, and recoils identified in the Argonne Fragment Mass Analyzer + ion chamber combination. Fig. 3 shows a spectrum of transitions in the ground state band of ^{76}Sr as observed in this work. The spectrum was produced by requiring that the recoils have $Z = 38$, and summing the spectra of γ-rays in coincidence with the four lowest energy transitions. Excited states are observed up to a tentative spin of 14^+.

The Sr nuclei in this region are known to have fairly large prolate deformations, and in principle, should be easier to interpret than the Kr nuclei that display shape coexistence at low spins. The best way to observe the alignments of the $g_{9/2}$ protons and neutrons for the Sr nuclei is to look at the dynamic moments of inertia, $J^{(2)}$, as a function of frequency. This is shown in Fig. 4a for ^{82}Sr [10], ^{80}Sr [11], ^{78}Sr [8] and ^{76}Sr. The $g_{9/2}$ proton alignments in ^{82,80,78}Sr are observed at $\hbar\omega \sim 0.55$ MeV. The new data for ^{76}Sr indicate a delay in the alignment relative to the heavier even-even Sr nuclei. Observation of an additional one or two γ-rays would clearly be helpful.

In a similar experiment, the ^{24}Mg(^{58}Ni,2*n*) reaction at a beam energy of 200 MeV was used to populate excited states in ^{80}Zr. States up to spin (12^+) have been observed in this study. Fig. 4b shows the kinematic moments of inertia, $J^{(1)}$, as a function of the square of the frequency for the nuclei ^{84}Zr [12], ^{82}Zr [13], and ^{80}Zr. While the alignments are clear for the heavier Zr nuclei, the data for ^{80}Zr show no sudden increase in the moment of inertia up to the highest observed transition.

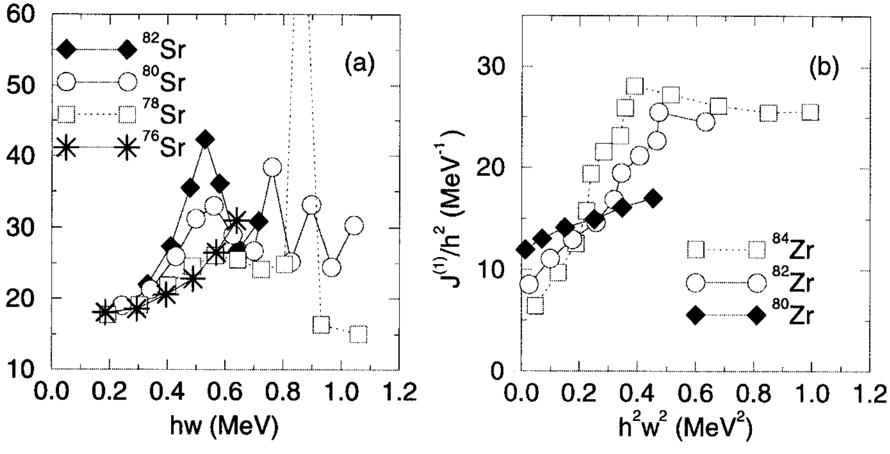

Fig. 4. The left panel (a) shows the dynamic moments of inertia as a function of frequency for the nuclei ^{82,80,78,76}Sr. The right panel (b) shows the kinematic moments of inertia as a function of the square of the frequency for the nuclei ^{84,82,80}Zr.

4. CONCLUSIONS

The ground state bands in the nuclei ^{72}Kr, ^{76}Sr and ^{80}Zr have been significantly extended from what has previously been observed. The alignment of $g_{9/2}$ neutrons and protons for ^{72}Kr is quite dramatically delayed relative to the predicted frequency. The data for both ^{76}Sr and ^{80}Zr indicate that the alignments for these nuclei are also delayed relative to the heavier even-even isotopes. The systematic delays in alignment of $g_{9/2}$ particles for these $N = Z$ nuclei suggest that *np* pairing correlations may play a significant role in this unexpected behavior. These *np* pairs may stabilize the nucleus to higher frequency, thus delaying the alignment of the $g_{9/2}$ particles beyond the expected frequency. An important step in our understanding will be the inclusion of *np* pairing in future CSM calculations, and the ability to systematically reproduce the results for these $N = Z$ nuclei.

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